

Measurements of Single and Double Spin Asymmetry in pp Elastic Scattering in the CNI Region with Polarized Hydrogen Gas Jet Target

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Abstract. Precise measurements of the single spin asymmetry, A_N and the double spin asymmetry, A_{NN} , in proton-proton (pp) elastic scattering in the region of four-momentum transfer squared $0.001 < -t < 0.032$ (GeV/c^2) have been performed using a polarized atomic hydrogen gas jet target and the RHIC polarized proton beam at 24 GeV/c and 100 GeV/c . The polarized gaseous proton target allowed us to achieve the measurement of A_{NN} in the CNI region for the first time. Our results of A_N and A_{NN} provide significant constraints to determine the magnitude of poorly known hadronic single and double spin-flip amplitudes at this energy.

Keywords: Elastic scattering, spin, coulomb nuclear interference

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Introduction. pp elastic scattering is one of the most fundamental reactions in particle-nuclear physics and is described in transition amplitudes by use of helicity of initial and final states. Requiring that the interaction is invariant under space inversion, time reversal and rotation in spin space, pp scattering in a given spin state is described in five independent transition amplitudes (ϕ_i , $i = 1 - 5$) as functions of the center-of-mass energy squared, s , and t [1]. The understanding of these amplitudes would provide crucial guidelines to investigate the reaction mechanism.

Each transition amplitude is described as a sum of the hadronic amplitude (ϕ_i^{had}) and the electro-magnetic amplitude (ϕ_i^{em}). In the small $-t$ region, ϕ_i^{em} and ϕ_i^{had} become similar in strength and interfere with each other. We call this interference the Coulomb Nuclear Interference (CNI). Thanks to the great successes of QED and the past pre-

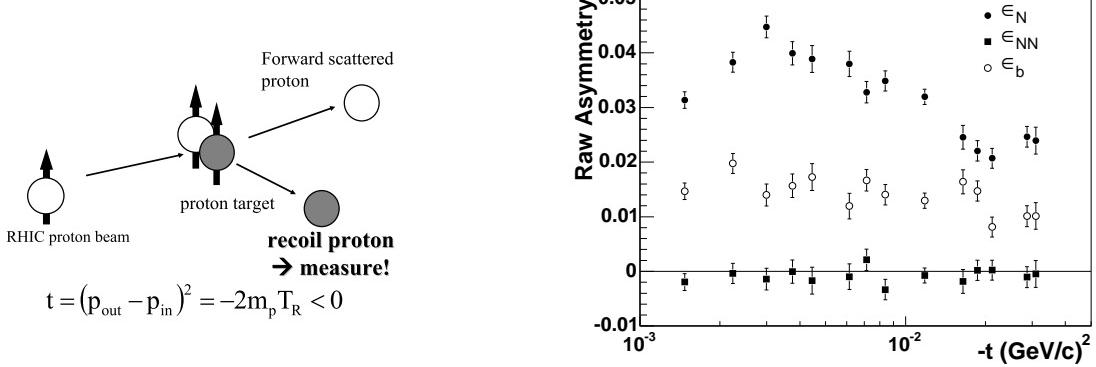


FIGURE 1. Left: Example of "parallel" case, $p^\uparrow p^\uparrow \rightarrow pp$. Right: ϵ_{NN} , ϵ_N and ϵ_b at $\sqrt{s} = 13.7$ GeV as a function of $-t$.

cisely measured quantities (ex. magnetic moment), ϕ_i^{em} is precisely described. On the other hand, ϕ_i^{had} is not fully described by theory, because the perturbative QCD is not applicable in the CNI region. By use of the experimental data of total and differential cross-section of unpolarized pp elastic scattering, we can determine the sum of two non-spin-flip hadronic amplitudes ($\phi_+^{had} = \phi_1^{had} + \phi_3^{had}$) [3]. In order to approach to the hadronic single and double spin-flip amplitudes (ϕ_5^{had} and ϕ_2^{had}), we measure A_N and A_{NN} in the CNI region. A_N is defined by the asymmetry of cross-section with up-down transverse polarization for one of the protons. Similarly A_{NN} is defined by the asymmetry of cross-section for parallel and anti-parallel transverse polarization for both of the protons. The left side of Fig. 1 depicts "parallel" case. We define the scattering plane from 3-momenta of incident and recoil particles, which is normal to the spin directions. By use of transition amplitudes, A_N is expressed as,

$$A_N \approx \frac{-\text{Im}[\phi_5^{em}(s, t)\phi_+^{had*}(s, t) + \phi_5^{had}(s, t)\phi_+^{em}(s, t)]}{|\phi_+(s, t)|^2}. \quad (1)$$

The first term of Eq. 1 is calculable and has a peak around $-t \simeq 0.003$ $(\text{GeV}/c)^2$ [2] which is generated by proton's anomalous magnetic moment. Because the presence of ϕ_5^{had} introduces a deviation in shape and magnitude from the first term, a measurement of A_N in the CNI region, therefore, can be a sensitive probe for ϕ_5^{had} .

A_{NN} is expressed as,

$$A_{NN} \approx \frac{2|\phi_5^{had}(s, t)|^2 + \text{Re}[(\phi_+(s, t))^*\phi_2^{had}(s, t)]}{|\phi_+(s, t)|^2}. \quad (2)$$

Because the first term is 2nd order of ϕ_5^{had} and the second term is 1st order of ϕ_2^{had} , A_{NN} is sensitive to ϕ_2^{had} [4]. From a consequence of angular momentum conservation at small $-t$ and large \sqrt{s} , we use $\phi_4^{had} \propto t \rightarrow 0$ for these expressions.

Experiment. Experiment has been performed using a polarized hydrogen gas jet target and polarized RHIC proton beam at 24 GeV/c ($\sqrt{s} = 6.7$ GeV) and 100 GeV/c ($\sqrt{s} = 13.7$ GeV). We detect the recoil protons by silicon detectors which are located on both sides of the target. The details of experimental setup are described in [5, 6].

In the pp elastic scattering process, both forward-scattered particle and recoil particle are protons and there are no other particles involved nor new particles produced in the process. Since initial states are well defined, the elastic process can be, in principle, identified by detecting the recoil particle only. By measuring kinetic energy T_R , time of flight, and recoil angle of recoil particle, we measure the mass of recoil particle and all the forward scattered rest particles. We collected 4.3 M events at $\sqrt{s} = 13.7$ GeV and 0.8 M events at $\sqrt{s} = 6.7$ GeV, respectively. The details of event selection is described in [5].

The selected event yield is sorted by $-t$ bins, which is obtained measuring the kinetic energy of the recoil particle: $-t = 2m_p T_R$, and spin states. m_p is the proton mass. Then we calculate two types of single spin *raw* asymmetries, ε_N for the target spin state and ε_b for the beam spin state. We also calculate double spin *raw* asymmetry, ε_{NN} for the target and beam spin states.

The right side of Fig. 1 displays these *raw* asymmetries of $\sqrt{s} = 13.7$ GeV data as a function of $-t$ in the region $0.001 \leq -t \leq 0.035$ (GeV/c)² ($0.5 \leq T_R \leq 17$ MeV). The polarized gaseous proton target allowed us to achieve the measurement in the CNI region for the first time. In order to cancel out the asymmetries of up-down luminosity, and detector acceptance, we employed so-called "square root formula" for ε_N and ε_b calculation. On the other hand, ε_{NN} needs to be corrected by the luminosity asymmetry. The target spin flips every 5 minutes and the density of both spin states are the same and stable during the experimental period (~ 90 hours). The beam intensity, which is measured by the wall current monitor [7], varies by bunch (every 106 nsec in 2004) and fill (every several hours). By accumulating intensity for the experimental period, the variation is compensated. Therefore the luminosity asymmetry is quite small compared to statistical error of ε_{NN} .

Results and discussions. A_N is measured normalizing ε_N by well measured the target polarization P_t [6],

$$A_N = \frac{\varepsilon_N}{P_t}. \quad (3)$$

Utilizing the measured A_N , we also measure the beam polarization, $P_b = \varepsilon_b/A_N$ ¹. Normalizing ε_{NN} by P_t and P_b , A_{NN} is obtained via

$$A_{NN} = \frac{\varepsilon_{NN}}{P_b P_t}. \quad (4)$$

The left and right plots of Fig. 2 display the results of A_N and A_{NN} at $\sqrt{s} = 6.7$ GeV with filled circles and 13.7 GeV with open circles, respectively. The errors on the data

¹ This experimental setup also plays an important role in the RHIC spin program to measure the absolute beam polarization [8].

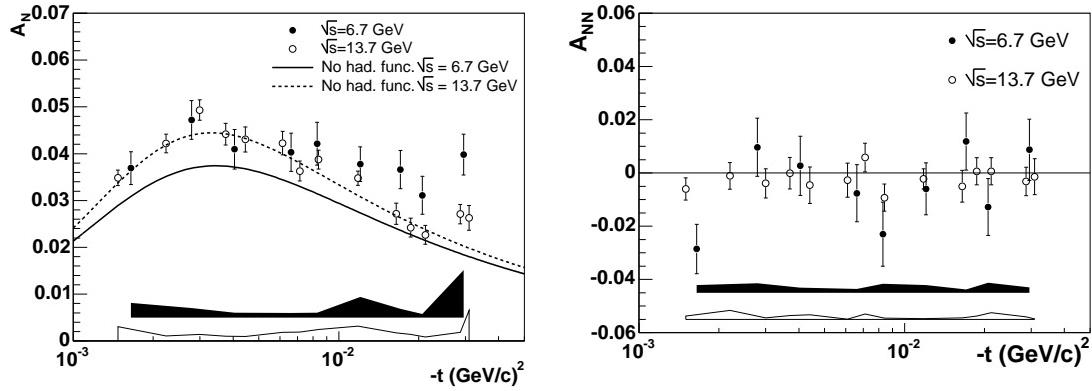


FIGURE 2. The left and right plots display the results of A_N and A_{NN} at $\sqrt{s} = 6.7 \text{ GeV}$ with filled circles and 13.7 GeV with open circles, respectively. The errors on the data points are statistical. The lower bands represent the total systematic errors. The solid and dashed lines in the left plots correspond to the first term in Eq. 1 for these \sqrt{s} , respectively.

points are statistical. The lower bands represent the total systematic errors. The solid and dashed lines correspond to the first term in Eq. 1 for these \sqrt{s} , respectively.

A_N at $\sqrt{s} = 13.7 \text{ GeV}$ are consistent with the dashed line ($\chi^2/\text{ndf}=13.4/14$). On the other hand, although the accuracy is statistically limited, A_N at $\sqrt{s} = 6.7 \text{ GeV}$ are *not* consistent with the solid line ($\chi^2/\text{ndf}=35.5/9$) and this discrepancy implies the presence of ϕ_5^{had} . A_{NN} for these \sqrt{s} have no clear $-t$ dependence and the average values are consistent with zero within 1.5σ .

In summary, measurements of A_N and A_{NN} provide experimental knowledge to poorly known ϕ_5^{had} and ϕ_2^{had} . The \sqrt{s} dependence of ϕ_5^{had} is provided by A_N results and the theoretical interpretation is under way [9]. However, there is no comprehensive understanding of ϕ_2^{had} and ϕ_5^{had} yet. Further measurements at different \sqrt{s} are required to fully describe the behavior of ϕ_2^{had} and ϕ_5^{had} .

REFERENCES

1. M. Jacob and G.C. Wick , Annals Phys. **7**, 404 (1959).
2. N.H. Buttimore *et al.*, Phys. Rev. D **59**, 114010 (1999).
3. M.M. Block and R.N. Cahn, Czech. J. Phys. **40**, 164-175 (1990).
4. T.L. Trueman, RHIC Spin Note, September 27, (2005), hep-ph/0604153.
5. H. Okada *et al.*, Phys. Lett. B **638**, 450 (2006); H. Okada, Doctororal thesis, July (2006); <http://www.star.bnl.gov/~hiromi/HiromiOkadaThesis.pdf>
6. A. Zelenski *et al.*, Nucl. Inst. and Meth. A **536**, 248 (2005); T. Wise *et al.*, Nucl. Inst. and Meth. A **559**, 1 (2006).
7. P.R. Cameron *et al.*, Nucl.Instrum.Meth. **A345**, 226-229 (1994).
8. K.O. Eyser, these proceedings (2006).
9. Private discussion with L. Trueman.